Natural explanation for 130 GeV photon line within vector boson dark matter model

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We present a dark matter model for explaining the observed 130 GeV photon line from the galaxy center. The dark matter candidate is a vector boson of mass m_V with a dimensionless coupling to the photon and Z boson. The model predicts a double line photon spectrum at energies equal to m_V and $m_V(1-m_Z^2/4m_V^2)$ originating from the dark matter annihilation. The same coupling leads to a mono-photon plus missing energy signal at the LHC. The entire perturbative parameter space can be probed by the 14 TeV LHC run. The model has also a good prospect of being probed by direct dark matter searches as well as the measurement of the rates of $h \to \gamma\gamma$ and $h \to Z\gamma$ at the LHC.

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Recently a monochromatic photon line at 130 GeV has been found in the FermiLAT data in the vicinity of the galactic center [1, 2]. A possible explanation for this line can be the annihilation of a Dark Matter (DM) pair of mass 130 GeV directly to a photon pair with cross section equal to 10^{-37} cm^2. Extensive studies have been carried out in the literature to explain this line [3, 4]. In these models, the DM is taken to be either a scalar or a fermion so the annihilation to a photon pair cannot take place at a tree level with renormalizable couplings. If the charged particles propagating in the loop are light enough, their direct production via DM annihilation typically exceeds the bounds [5].

However, within Vector Dark Matter (VDM) models novel features appear. Such VDM models have recently received attention in the literature [6, 7]. Here, we show that the vector boson DM candidate has a unique advantage for explaining the 130 photon line because unlike a neutral scalar or spinor, a neutral vector boson can directly couple to photon through a large unsuppressed dimensionless gauge invariant coupling. In this letter, we introduce a simple model that explains the 130 GeV line. The model predicts accessible new signals for the LHC and can explain the slight excess of $Br(h \to \gamma\gamma)$. In sec. I, we introduce the model and discuss the direct and indirect DM searches within this model. In sec. II, we compute the contribution to the Higgs decay to a photon pair. In sec. III, we discuss the potential signal at colliders. Results are summarized in sec. IV.

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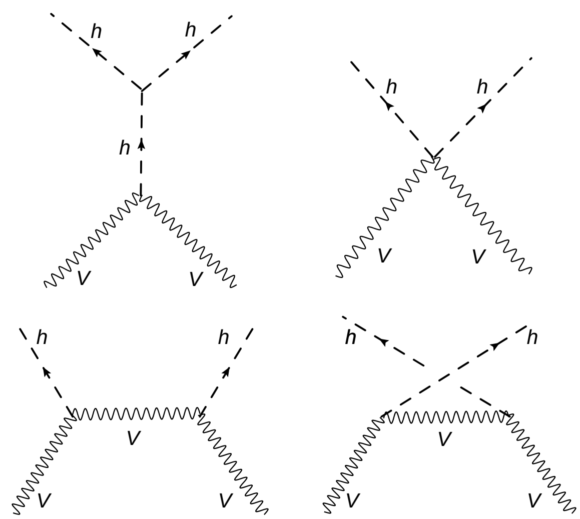

FIG. 1: Annihilation of the V pair to a Higgs pair via λ_1 coupling

I. THE MODEL

The model adds only a pair of neutral vector bosons V and V' with masses $m_V < m_{V'}$ to the Standard Model (SM). We impose a Z_2 symmetry under which only V and V' are odd so V is stable and therefore a potentially suitable dark matter candidate. To avoid negative norm modes, we take their kinetic terms to be of antisymmetric form: *i.e.*, $-\left[V_{\mu\nu}V^{\mu\nu}+V'_{\mu\nu}V'^{\mu\nu}\right]/4$ where $V^{(\prime)}_{\mu\nu} \equiv \partial_\mu V^{(\prime)}_\nu - \partial_\nu V^{(\prime)}_\mu$. In general, V_μ and V'_μ can have mixed mass of form $V_\mu V'^\mu$ as well as a coupling of form $V'_\mu V^\mu |H|^2$. Without loss of generality, we can go to a basis where V_μ and V'_μ are mass eigenstates with mass eigenvalues m_V and $m_{V'}$. In this basis, the dimension-

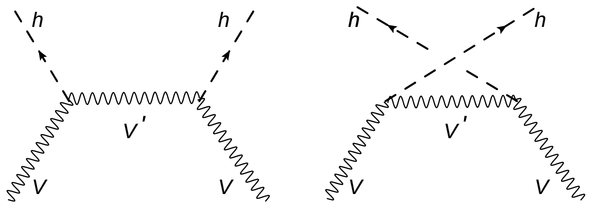

FIG. 2: Annihilation of the V pair to a Higgs pair via the λ_3 coupling

less gauge and Z_2 invariant couplings to the Higgs are

$$\frac{\lambda_1}{2}|H|^2 V_\mu V^\mu + \frac{\lambda_2}{2}|H|^2 V'_\mu V'^\mu + \lambda_3 |H|^2 V'_\mu V^\mu. \qquad (1)$$

Although the λ_i couplings are dimensionless, if V_μ are not gauge bosons, they will be non-renormalizable [8]. We can promote V_μ and V'_μ to gauge bosons of two new $U(1)$ gauge symmetries as prescribed in the Stückelberg mechanism, by replacing V_μ and V'_μ in these terms as well as in mass terms with $\partial_\mu\theta_V - V_\mu$ and $\partial_\mu\theta_{V'} - V'_\mu$. We will work in a gauge that the Stückelberg fields θ_V and $\theta_{V'}$ are eaten by the longitudinal components of V and V'. For the purpose of this paper, it is enough to take λ_i Wilsonian effective couplings below some cutoff Λ. The new vector boson can have quartic couplings with each other but these couplings are not relevant for our discussion. Notice that λ_i should be real to guarantee the Hermiticity of the potential; however, because of the presence of quartic vector boson coupling, we do not know a priori their sign.

The λ_1 and λ_3 couplings give rise to annihilation of to the V pair (see Figs 1,2). Setting $\lambda_3 = 0$, we find

$$\langle \sigma(VV \to hh) v_{rel}\rangle = \frac{\lambda_1^2\sqrt{m_V^2 - m_h^2}}{576\pi m_V^3}$$

$$\{\frac{[(4m_V^2 - m_h^2)(m_V^2 + 2\lambda_1 v_h^2) - \frac{3}{2}\tan\theta_W m_V^2 m_h^2]^2}{m_V^4(m_H^2 - 4m_V^2)^2} + 2[1 + \frac{2\lambda_1 v_h^2}{2m_V^2 - m_h^2} + \frac{3\tan\theta_W m_h^2}{2(-4m_V^2 + m_h^2)}]^2\} \qquad (2)$$

The vacuum expectation value of Higgs is denoted by $v_h = 246$ GeV. Moreover, like other Higgs portal models, the λ_1 coupling gives rise to the annihilation of the V pair via an s-channel Higgs exchange diagram with cross section

$$\langle \sigma(VV \to f\bar{f}) v_{rel}\rangle = \frac{\lambda_1^2 v_h^2 \Gamma(h^* \to f\bar{f})}{3m_V(4m_V^2 - m_h^2)^2},$$

where $f\bar{f}$ can be W^+W^-, ZZ, $b\bar{b}$ and etc. $\Gamma(h^* \to f\bar{f})$ is the decay rate of a hypothetical SM-like Higgs (h^*) with a mass equal to $2m_V$ to $f\bar{f}$. To account for the observed dark matter abundance within the thermal production scenario [9], the total DM pair annihilation cross section should be equal to 1 pb. Setting the sum of cross sections of these two modes equal to 1 pb and $m_V = 130$ GeV, we find $\lambda_1 = 0.12$. The λ_3 coupling also gives rise to annihilation to a Higgs pair via a $t-$ and $u-$ channel V' exchange (see Fig.2). Fixing $\lambda_1 = 0$, we find

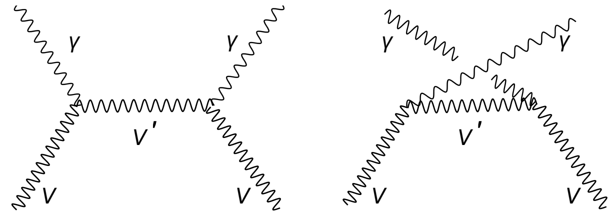

FIG. 3: Annihilation of the V pair to a photon pair

$$\langle \sigma(VV \to hh) v_{rel}\rangle = \frac{\lambda_3^4 v_h^4\sqrt{m_V^2 - m_h^2}}{144\pi m_V^3} \{\frac{1}{m_{V'}^4} + \frac{2}{(m_V^2 - m_h^2 + m_{V'}^2)^2}\}. \qquad (3)$$

Taking $\sigma(VV \to hh) = 1$ pb, for $\lambda_1 = 0$ and $m_V = 130$ GeV, we find $\lambda_3 \simeq 0.4(m_{V'}/300 \text{ GeV})$. Notice that for $\lambda_1 = 0$ and $m_{V'} > O(3 \text{ TeV})$ the required λ_3 enters the non-perturbative regime.

The Lagrangian can also include the following term with dimensionless coupling:

$$g_V B^{\mu\nu} V_\mu V'_\nu \; ,$$

where $B^{\mu\nu}$ is the field strength associated with the hypercharge gauge boson: $B_{\mu\nu} = \cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}$. Again although g_V is dimensionless, if V_μ and V'_μ are not promoted to gauge bosons, this coupling is non-renormalizable [10]. Again using the Stückelberg mechanism this term can be made gauge invariant. This coupling can arise by integrating out heavy chiral fermions charged both under hypercharge and the new $U(1)$ gauge symmetries. The g_V coupling can be large contrary to the non-decoupling theorem [10]. A similar term has also been employed in [3] to explain the 130 GeV line. This coupling leads to (see Fig.3)

$$\langle \sigma(V + V \to \gamma\gamma) v_{rel}\rangle = \frac{g_V^4 \cos^4\theta_W}{72\pi} \frac{2 + 8x + 9x^2}{m_V^2 x^2 (1+x)^2}$$

where $x = (m_{V'}/m_V)^2$ and

$$\langle \sigma(V + V \to \gamma Z) v_{rel}\rangle = \frac{g_V^4 \sin^2 2\theta_W (4y-1)^3 f(y, y')}{9\pi 2^{12} m_Z^2 y^4 y'^2 (1 - 2y - 2y')^2}$$

where

$$f(y, y') = 32y^4 + y'^2 + 16y^3(8y' - 3)$$

$$+6y^2(24y'^2 - 16y' + 3) + y(8y'^2 - 8y' + 1)$$

in which $y = (m_V/m_Z)^2$ and $y' = (m_{V'}/m_Z)^2$. We therefore expect two photon lines: one photon line at

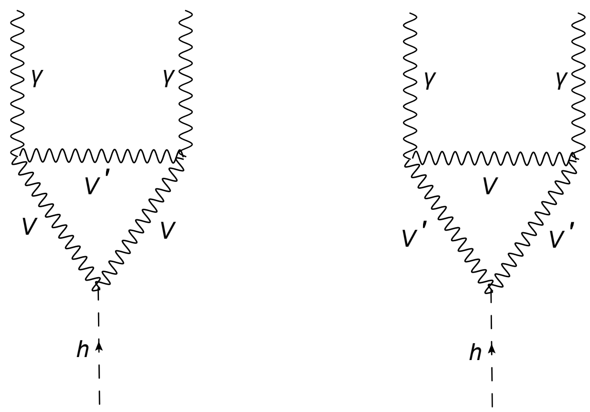

FIG. 4: Diagrams of Higgs decay to a photon pair via the λ_1 and λ_2 couplings

m_V and another at $m_V(1 - m_Z^2/4m_V^2)$ with an intensity suppressed by $\sigma(V + V \to \gamma Z)/[2\sigma(V + V \to \gamma\gamma)] < (\tan^2\theta_W) = 0.3$. In fact, observation favors double line structure over a single line [2]; however, more data is required to resolve such a double line feature [11]. From now on we take $m_V = 130$ GeV and $\sigma(V + V \to \gamma\gamma) = 10^{-37}$ cm^2 which for $m_{V'} = 200$ GeV yields $g_V = 0.19$ and for $m_{V'} \geq 300$ GeV yields $g_V \simeq 0.27(m_{V'}/300 \text{ GeV})$. As long as $m_{V'} <$a few TeV, required value of g_V will remain in the perturbative regime.

Through the λ_1 coupling, the dark matter interacts with nuclei with cross section of

$$\sigma_{SI}(V + N \to V + N) = \frac{\lambda_1^2 f^2}{4\pi}\frac{m_N^2 m_r^2}{m_V^2 m_h^4}$$

where m_N is the mass of a nucleon and $m_r = m_N m_V/(m_V + m_N)$ is the reduced mass for the collision. f parameterizes the nuclear matrix element ($0.14 < f < 0.66$) [12]. Taking $\lambda_1 = 0.12$, we find $\sigma = 4.4 \times 10^{-45}(f/0.2)^2$cm^2. This means under the condition that λ_1 is the main contributor to the DM annihilation, the present bound from XENON100 [13] practically rules out $f > 0.2$. However for $\lambda_1 \ll \lambda_3 \simeq 0.5(m_{V'}/300 \text{ GeV})$, we do not expect an observable effect in the direct searches. If the mass splitting between V and V' is smaller than $O(100 \text{ keV})$, the DM can interact inelastically with the g_V coupling through a t-channel photon exchange. Small splitting can be justified by an approximate $V \leftrightarrow V'$ symmetry. We do not however consider such a limit so the main interaction will be via the Higgs portal channel.

II. HIGGS DECAY TO A PHOTON PAIR

The λ_1 and λ_2 couplings contribute to $h \to \gamma\gamma$ via triangle diagrams within which V and V' propagate (see Fig.4). The leading-log contribution of λ_1 to the decay amplitude is

$$M(h \to \gamma\gamma) = \frac{v_h \lambda_1 (g_V \cos\theta_W)^2}{8\pi^2} g(x,z) \log\frac{\Lambda^2}{m_{V'}^2},$$

where $g(x,z) \equiv (13z - 5z^2/8 + z/x - 3x^2)$, $z = (m_H/m_V)^2$ and $x = (m_{V'}/m_V)^2$. Replacing $\lambda_1 \to \lambda_2$ and $m_V \leftrightarrow m_{V'}$, we obtain the contribution of λ_2. These amplitudes have to be summed up with the SM triangle diagrams within which top quark and W boson propagate. Notice that our result is ultra-violet divergent. This is because g_V and λ_1, despite being dimensionless, are non-renormalizable [8]. For $\lambda_1 \log\Lambda^2/m_{V'}^2 \sim 1$, the contribution of λ_1 will be comparable to that in the SM. The observed slight excess [14] can be attributed to this effect. Notice that if the excess is confirmed, the sign of λ_1 can also be determined. If further data rules out the excess, a bound on $\lambda_1 \log\Lambda^2/m_{V'}^2$ can be derived which for the value of λ_1 found in previous section ($\lambda_1 = 0.12$) can be interpreted as an upper bound on Λ. That is the scale of new physics giving rise to the effective g_V coupling can be constrained. In case that λ_3 is the main contributor to the dark matter annihilation, the effect of λ_1 can be arbitrarily small. As discussed, these two possibilities can be distinguished by direct dark matter searches.

With similar diagrams we predict a contribution to $H \to Z\gamma$. Since in this model the new particles are heavier than m_h, the Higgs cannot have invisible decay modes.

III. DIRECT PRODUCTION AT THE COLLIDERS

A pair of V and V' can be produced by the annihilation of a fermion (f) and antifermion ($\bar{f}$) pair via a s-channel photon exchange,

$$\sigma(f\bar{f} \to VV') = \frac{(eQ_f g_V \cos\theta_W)^2}{192\pi N_c}\mathcal{K}[E_{cm}^2 + 2(m_V^2 + m_{V'}^2)]$$

$$\times \frac{[(E_{cm} - m_{V'})^2 - m_V^2][(E_{cm} + m_{V'})^2 - m_V^2]}{E_{cm}^6 m_V^2 m_{V'}^2} \quad (4)$$

where $\mathcal{K} = \sqrt{(E_{cm}^2 + m_V^2 - m_{V'}^2)^2 - 4m_V^2 E_{cm}^2}$. Notice that the behavior of the cross section for $E_{cm} \to \infty$ violates unitarity. This is because g_V is an effective coupling below Λ. There is also a subdominant contribution from $gg \to h^* \to VV'$ which can be neglected relative to $f\bar{f} \to \gamma^* \to VV'$. The energy of center in the LEP experiment was too low to allow the production of V and V' pair. However, in the LHC, the V and V' pair can be produced as long as we are in the perturbative regime; *i.e.*, as long as $m_{V'} <$few TeV.

Regardless of the mass range, V' can decay to a photon and V:

$$\Gamma(V' \to V + \gamma) = \frac{g_V^2 \cos^2\theta_W}{96\pi}\frac{(m_{V'}^2 - m_V^2)^3(m_{V'}^2 + m_V^2)}{m_V^2 m_{V'}^5}.$$

The signature of the $V + V'$ production at the LHC will hence be an energetic mono-photon plus missing energy which has only low background [15] and therefore enjoys a good discovery chance. There is also a decay mode to $V + Z$ suppressed by $\tan^2\theta_W$. If the kinematics allows V' can decay to $V + H$, $V + W^- + W^+$ and $V + 2H$, however, the decay into $V + \gamma$ will dominate. Using the parton distribution functions in [16], we have calculated $\sigma(pp \to VV')$ and found

that for $\sqrt{s} = 7$ TeV and $m_{V'} = 200$ GeV (and therefore $g_V = 0.19$), $\sigma(p + p \to V + V') = 50$ fb which seems to be already excluded by the 7 TeV run of the LHC [15]. However, to draw a conclusive result a dedicated analysis with customized cuts is necessary. Taking $\sqrt{s} = 8$ TeV(14 TeV) and $m_{V'} = 1.5$ TeV and therefore $g_V = 1.35$, we have found $\sigma(p+p \to V + V') = 0.5$ fb(90 fb) which means the LHC can probe almost the whole perturbative regime.

Pairs of $V + V$ can be produced via $gg \to h^* \to VV$ at the LHC. For $\lambda_1 = 0.14$, we have found the cross section to be 0.6 fb (2 fb) for 8 TeV (14 TeV) c.o.m energy.

IV. CONCLUSIONS

We have presented a model within which dark matter is composed of a new vector boson (V) of mass 130 GeV such that through its annihilation the observed 130 GeV photon line from the galaxy center can be explained. The model also contains another vector boson (V') which together they can couple to the antisymmetric field strengths of the photon and Z boson. This coupling leads to the annihilation of dark matter pair to two monochromatic lines: one line at 130 GeV and the other with an intensity suppressed relative to the first one by $\sigma(VV \to \gamma Z)/[2\sigma(VV \to \gamma\gamma)] < 0.3$ at 114 GeV. Thus, by searching for such double line feature the model can be tested. V' has to have a mass smaller than a few TeV to account for the 130 GeV line in the perturbative regime. The same coupling can also lead to $V + V'$ pair production at the LHC which will appear as mono-photon plus missing energy signal. For a given V' mass, the production rate is fixed. The present data seems to already rule out light V'. The entire perturbative region with $m_{V'} < 1.5$ TeV can be probed by the 14 TeV run of the LHC so this model is falsifiable with this method, too.

Within this model the dark matter pair mainly annihilates to a Higgs pair with a cross section equal to 1 pb to account for the observed dark matter abundance within the thermal dark matter scenario. This annihilation can take place with either λ_1 coupling or the λ_3 coupling defined in Eq. (1). If λ_1 is responsible for this annihilation, we expect an observable effect in near future in direct searches for dark matter. In fact, the present bound on dark matter-nucleon scattering cross section can be accommodated only with small form factor. λ_1 can also explain the small excess observed in $h \to \gamma\gamma$. It can also contribute to $h \to Z\gamma$. These observations can fix the sign of λ_1. However, if $\lambda_1 \ll \lambda_3$, such effects in the Higgs decay as well as direct dark matter searches disappear.

The couplings that lead to dark matter pair annihilation to the Higgs pair and $\gamma\gamma$ pair are all dimensionless. Nonetheless, if the vector bosons are not gauge bosons, they will be non-renormalizable leading to ultraviolet infinities and violation of unitarity. Thus, these couplings are only effective at low energies. However, as shown in [10], they can be large. Using the Stückelberg mechanism, these vector bosons can be made $U(1)$ gauge bosons, removing the cut-off dependence of $h \to \gamma\gamma$ and violation of unitarity in the $V+V'$ production at large center of mass energies.

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